

PHMSA Risk Model Work Group Meeting

Washington DC – August 9 to 11, 2016

Methods for Probability Estimation

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C-FER Technologies

- Qualitative vs. quantitative risk
- Quantitative probability methods
 - Analysis considerations
 - Statistical approach
 - Model-based approach
- Summary

- Qualitative vs Quantitative
 - Qualitative methods
 - Characterize without quantifying risk
 - Suited to threat identification and risk ranking
 - Quantitative methods
 - More objective basis for decision making
 - Suited to determining what action is required (if any) and when
- Quantitative risk requires quantitative probability estimates

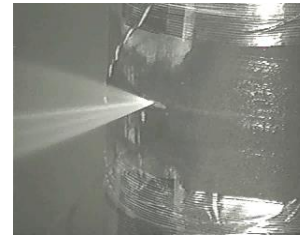
- Considerations
 - Failure causes
 - Failure modes
 - Failure measures

- Time-dependent
 - External corrosion
 - Internal corrosion
 - Stress Corrosion Cracking
- Stable / Resident → time-dependent
 - Manufacturing defects
 - Fabrication defects
 - Equipment malfunction
- Time-independent
 - Mechanical damage
 - Incorrect operation
 - Weather and outside force

From ASME B31.8S

Failure Modes

- Small leak
 - Small hole
 - Example: corrosion pin hole
- Large leak
 - Significant hole
 - Example: puncture or corrosion defect burst without extension
- Rupture
 - Full bore release
 - Example: defect burst with significant extension or girth weld separation

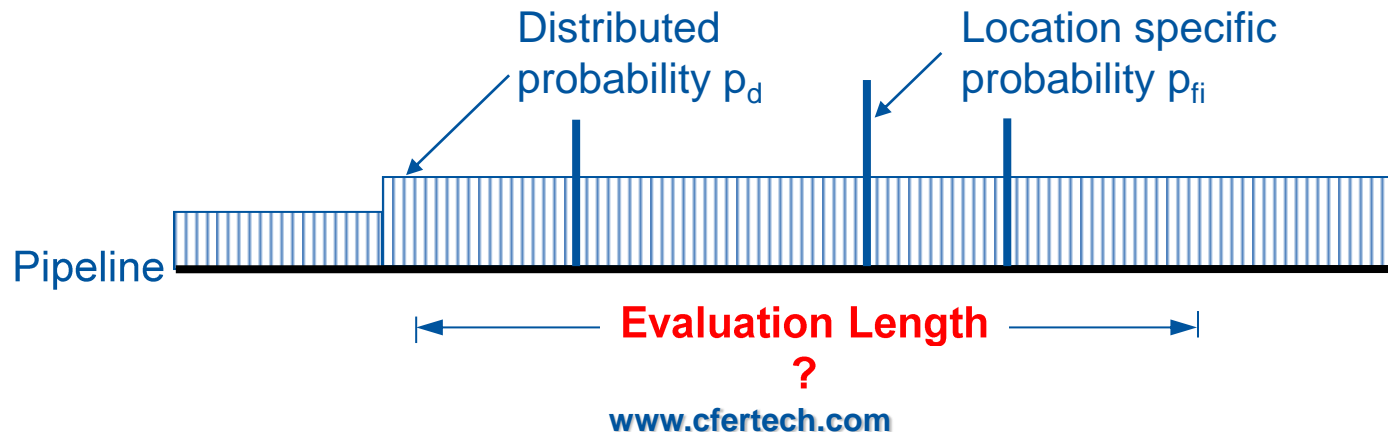


Increasing
consequences



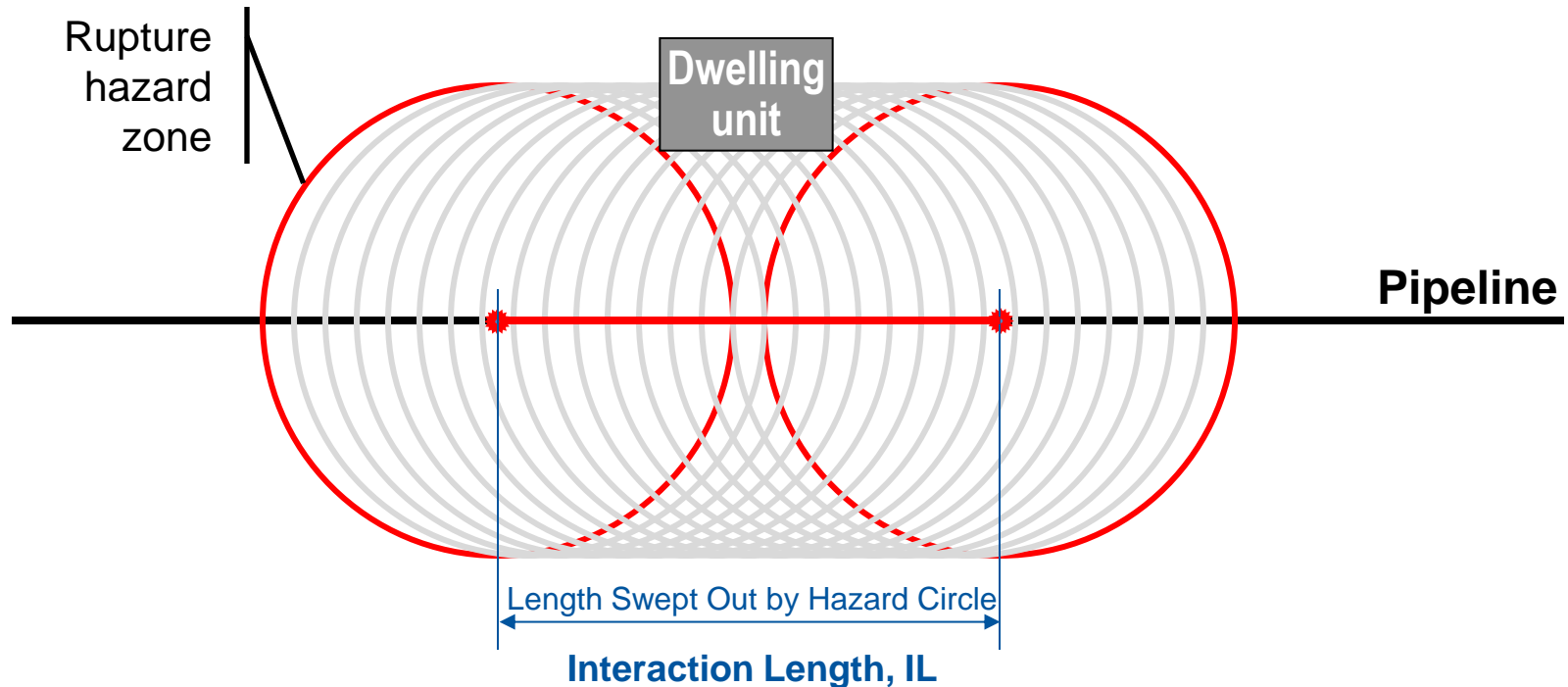
Linear system considerations

- Some integrity threats are concentrated at explicit locations
 - Locations known (e.g. corrosion defects found during inspection)
 - Best evaluated as discrete, location-specific probability
- Some integrity threats are distributed along pipeline length
 - Locations not known (e.g. future mechanical damage, corrosion defects not found)
 - Best evaluated as failure rate or distributed probability



Evaluation Length Considerations

- Example: safety implications of natural gas pipeline

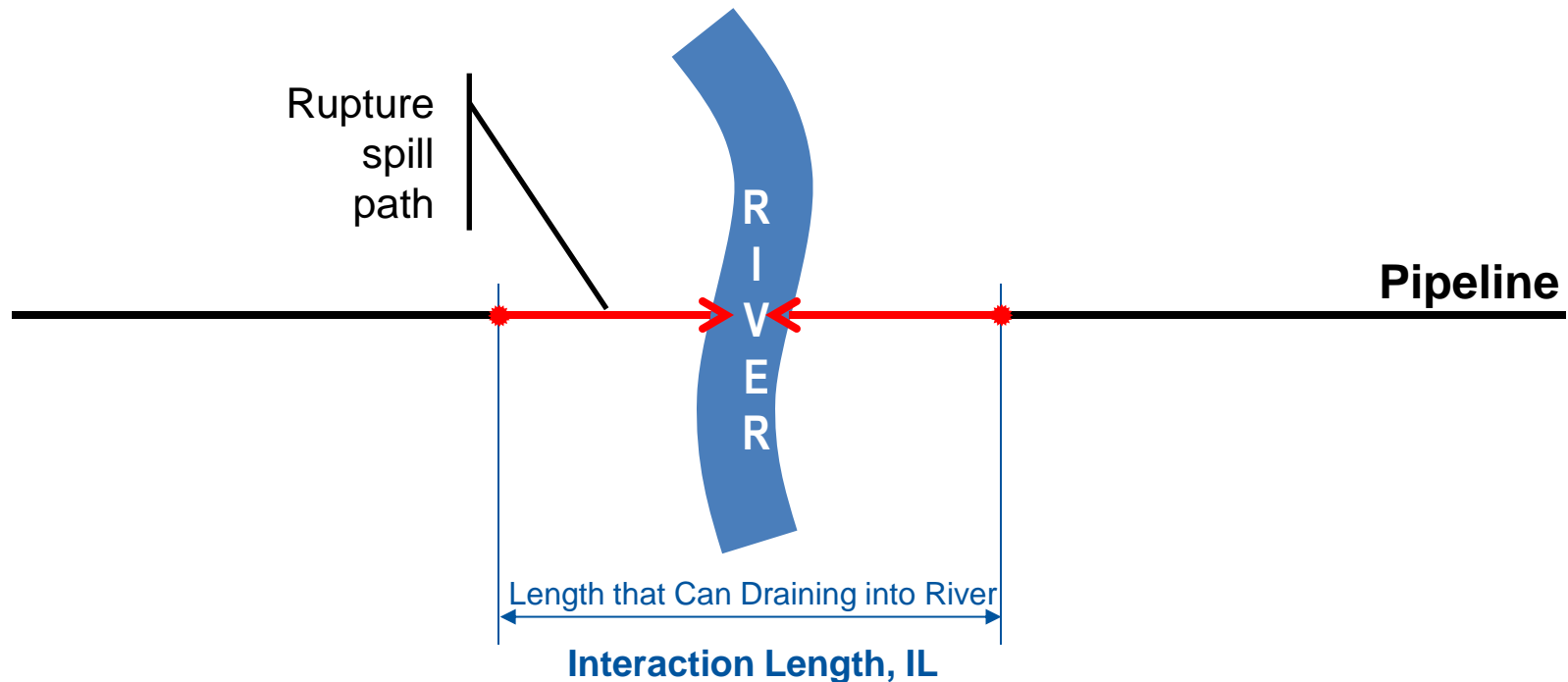


Interaction Length is segment length with potential to affect dwelling occupants

- occupants level of safety depends on reliability of entire IL
- level of safety depends on aggregated reliability of all defects within IL

Evaluation Length Considerations

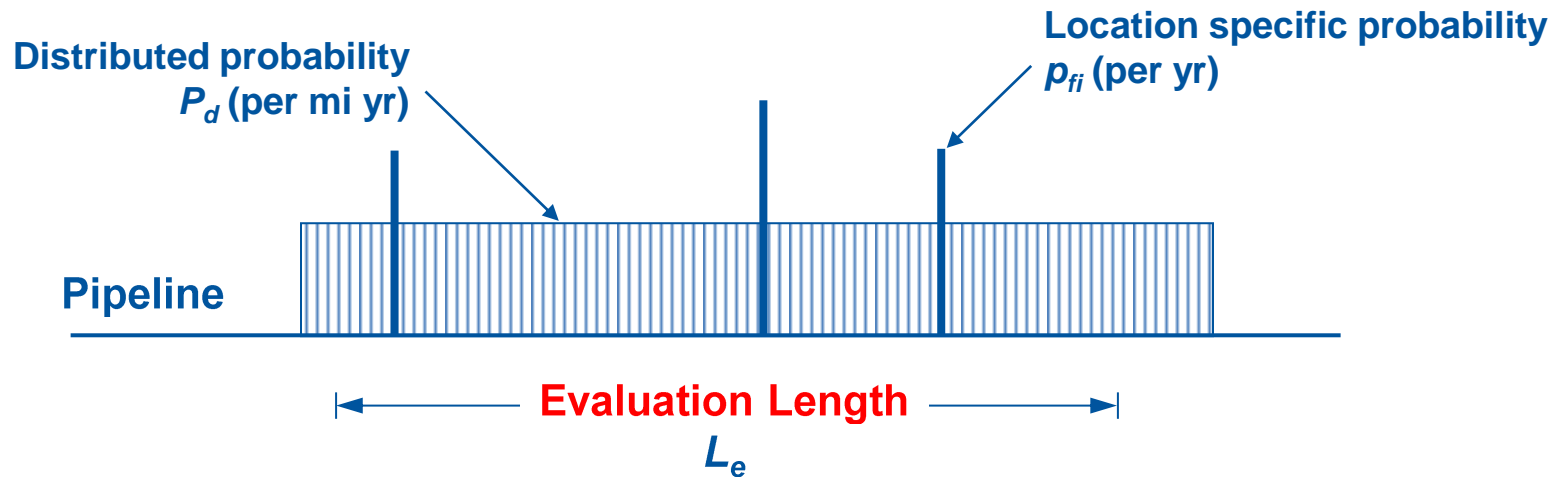
- Example: environmental implications of LVP pipeline



Interaction Length is segment length with potential to impact river

- level of environmental protection depends on reliability of entire IL
- level of protection depends on aggregated reliability of all defects within IL

- Evaluation length = interaction length



$$P_f = p_d + \frac{1}{L_e} \sum_{i=1}^n p_{fi}$$

← Failure rate or frequency
Units are failures per unit length per unit time
(e.g. per mile-year)

- Quantitative options
 - Statistical methods
 - Estimates developed from historical incident data
 - Model-based methods
 - Estimates developed from pipeline and ROW attributes using various models including structural reliability methods

- Approach
 - Collect historical data on previous pipeline failures
 - Use historical data as basis for probability estimates
- Data sources
 - Operator data
 - Industry data
 - US: US Department of Transportation (USDOT / PHMSA)
 - Canada: National Energy Board (NEB)
 - Europe: European Gas Pipeline Incident Group (EGIG)
UK Onshore Pipeline Operators Ass'n (UKOPA)
CONservation of Clean Air and Water in Europe (CONCAWE)

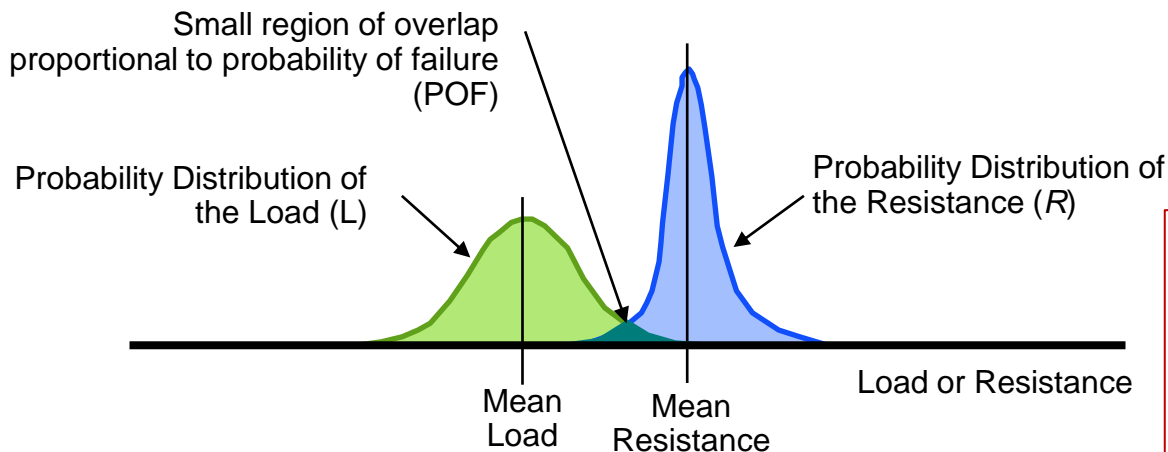
Calculate annual probability of corrosion rupture for a section of natural gas pipeline

- Consider incident database
 - 100,000 mi of gas transmission lines
 - 50 corrosion failures in last 5 years
 - 45% of corrosion failures are ruptures
- Solution
 - System exposure = 100,000 mi x 5 yr = 500,000 mi-yrs
 - Annual failure rate = incidents / exposure = 50 / 500,000 = 1×10^{-4} per mi-yr
 - Annual rupture rate = $0.45 \times 1 \times 10^{-4}$ per mi-yr = 4.5×10^{-5} per mi-yr
- Key assumption
 - Historical average is representative of line in question going forward
 - But what about impact of things like: line attributes/line condition/operating stress/integrity management actions?

Statistical Methods - Summary

- Advantages
 - Simple
 - Credible (based on *real* data)
- Limitations
 - Generally not pipeline-specific
 - Public data sets do not usually support subdivision by: diameter, thickness, age, operating stress, line condition, land use, etc.
 - Cannot account for maintenance actions
 - No link between failure rate and maintenance actions
 - Ignores systematic changes in pipeline condition
 - Cannot account for time-dependent deterioration
- Limitations can be addressed by introducing “adjustment factors” → usually involves judgment

- Approach
 - Develop failure prediction models that define the sets of conditions that can lead to failure → necessarily threat-specific
 - Use structural reliability methods where appropriate to combine deterministic models with input uncertainties to estimate probability (or frequency) of failure for individual threats



$$\text{POF} = P(R < L)$$

Central to the methodology is a formal characterization of the uncertainties inherent in both the applied load and the available resistance for each damage/deterioration mechanism (i.e. each threat)

Uncertainties Inherent in the Integrity Estimation Process

- Random variations → Loads imposed on the line
 - Internal pressure
 - Third party impact force
- Measurement uncertainty → Pipe properties & line condition
 - Joint-by-joint yield strength & fracture toughness
 - Number and size of defects
 - Defect growth rates
- Model uncertainty → Pipe behavior under loads
 - Model assumptions and approximations

Basis for Models - Consider the Integrity Management Process

- Management of progressive (time dependent) damage
 - Assess existing damage severity
 - Detect and size existing damage
 - Assess anticipated behavior over time
 - Estimate rate of growth and assess time for damage to become failure critical
 - Manage integrity
 - » Through periodic inspection and remediation or proof-testing
- Management of random (time independent) damage
 - Assess likelihood of event occurrence
 - E.g. quantify third-party hit frequency or seismic event likelihood
 - Assess anticipated pipe response to loading event
 - Quantify damage tolerance
 - Manage integrity
 - Through control of event likelihood and/or potential for failure given event

Time-dependent damage

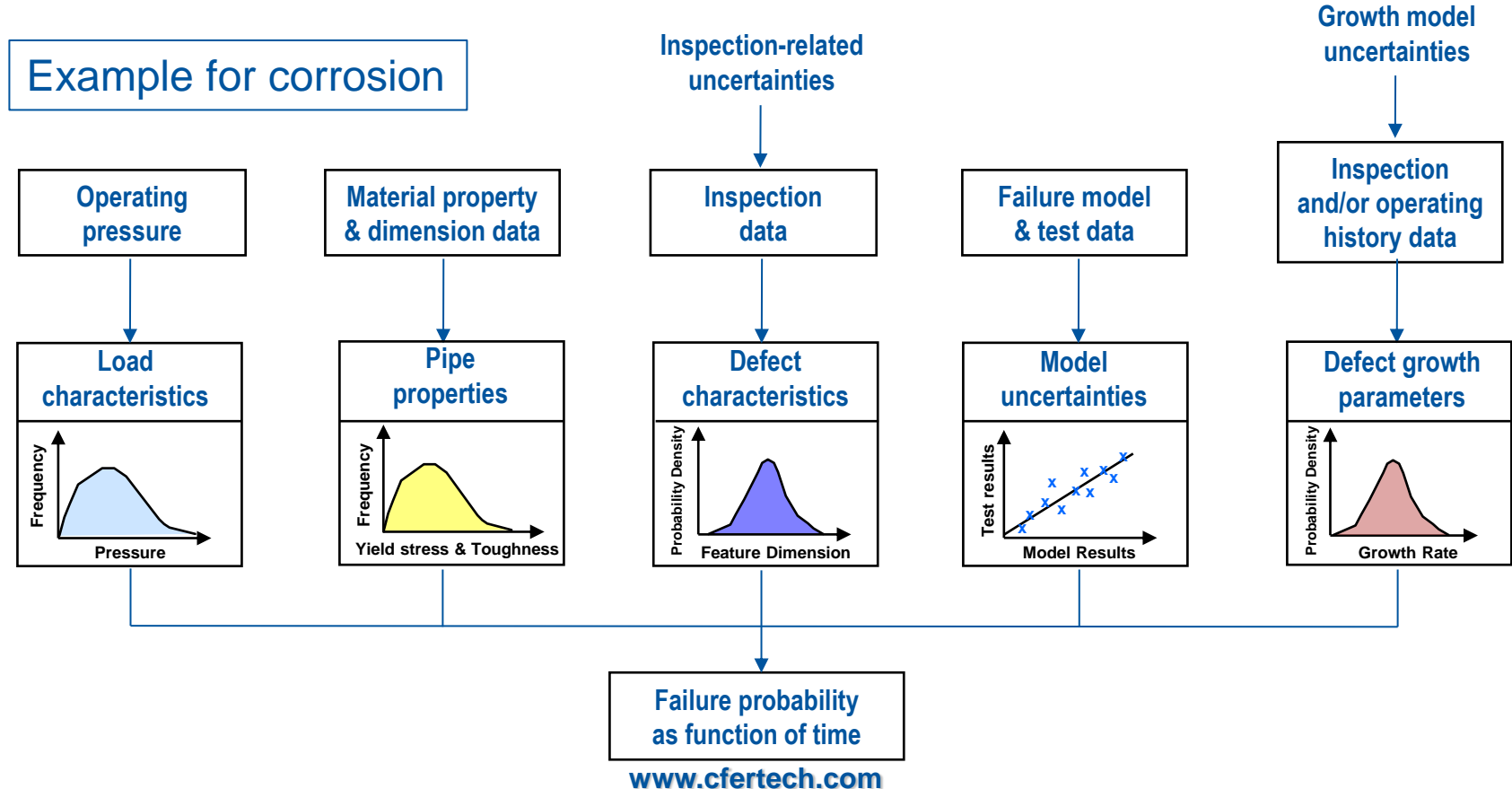
(e.g. corrosion, cracks, or progressive ground movement)

$$\text{Failure rate (per mi-yr)} = \text{No. defects (per mi)} \times \text{POF per defect (per yr)}$$

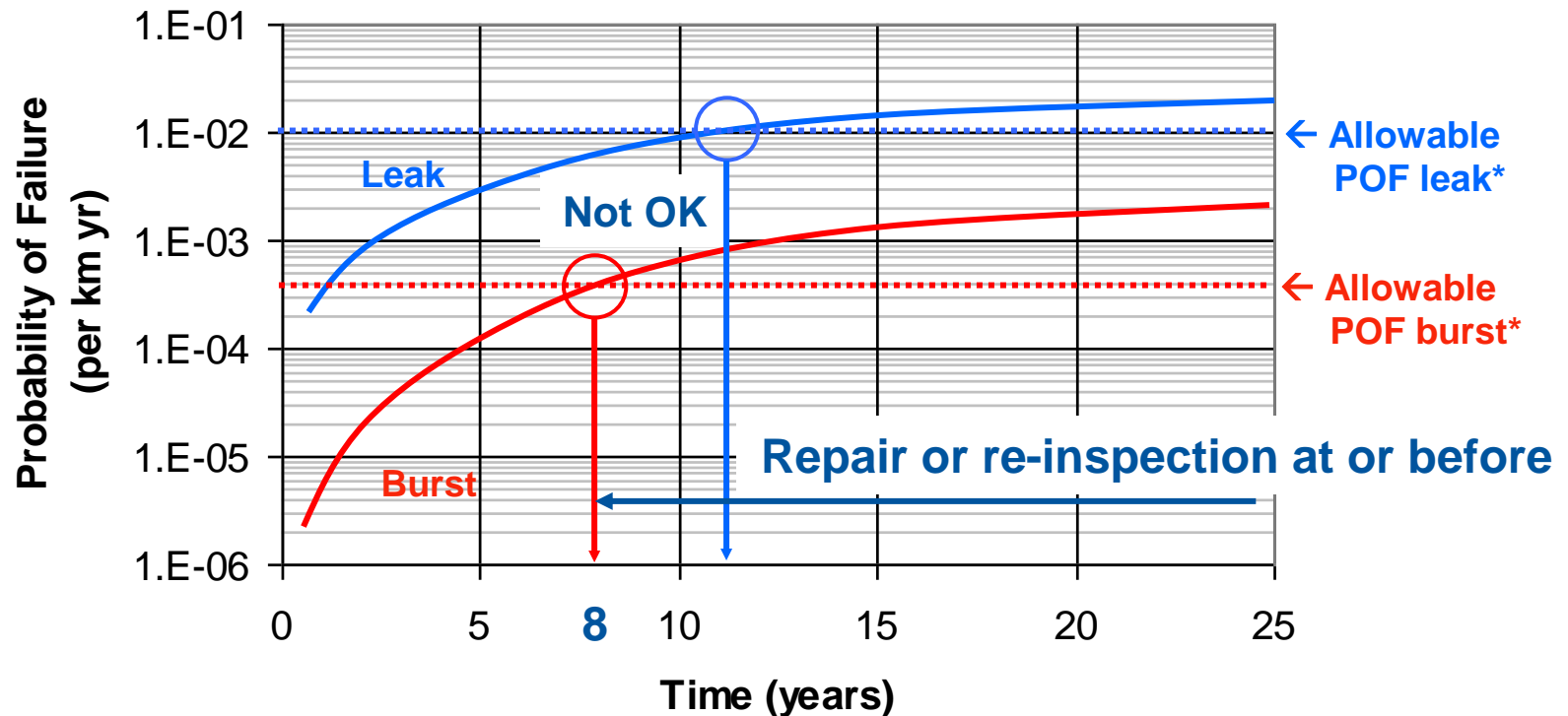
- Considerations in developing failure rate estimate (e.g. corrosion)
 - Characterization of defect population
 - Assumed actual number of features and feature sizes reflects the probability of detection and sizing accuracy of inspection method
 - Probability of failure over time ← structural reliability model
 - Failure projections reflect uncertainty in defect growth rates, variability in pipe properties, and accuracy of the failure prediction model
- Ability to reflect the impact of maintenance (e.g. corrosion)
 - Effects of defect remediation, re-inspection interval and/or modified operating pressure are directly reflected in probability estimates

Failure Probability Estimation

- Select deterministic failure prediction models (consider leak and burst separately)
- Formally characterize parameter/model uncertainties using probability distributions
- Calculate defect failure probability using standard techniques (e.g. simulation)



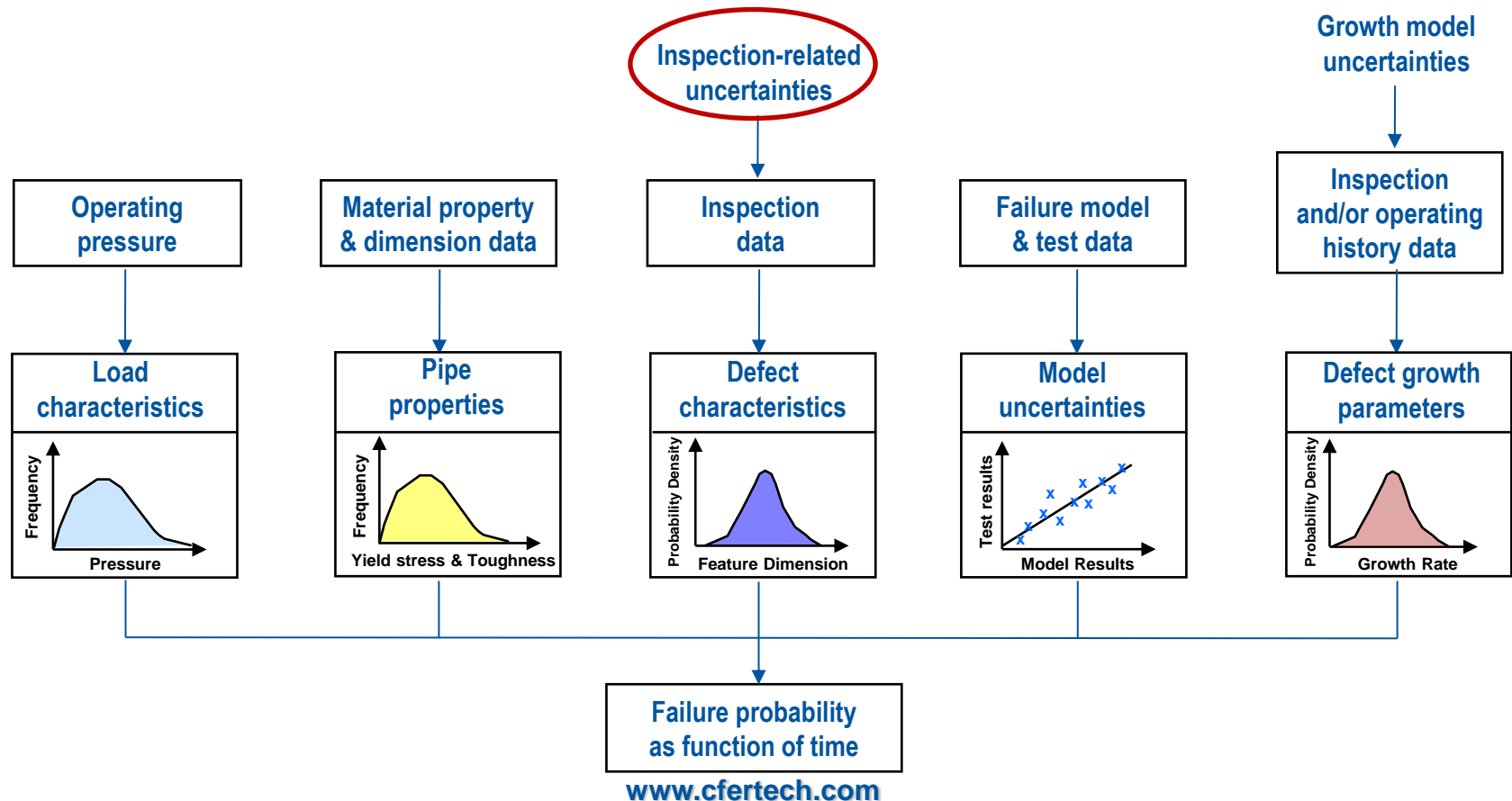
Segment reliability versus time – for given evaluation length



**based on risk considerations considering failure consequences*

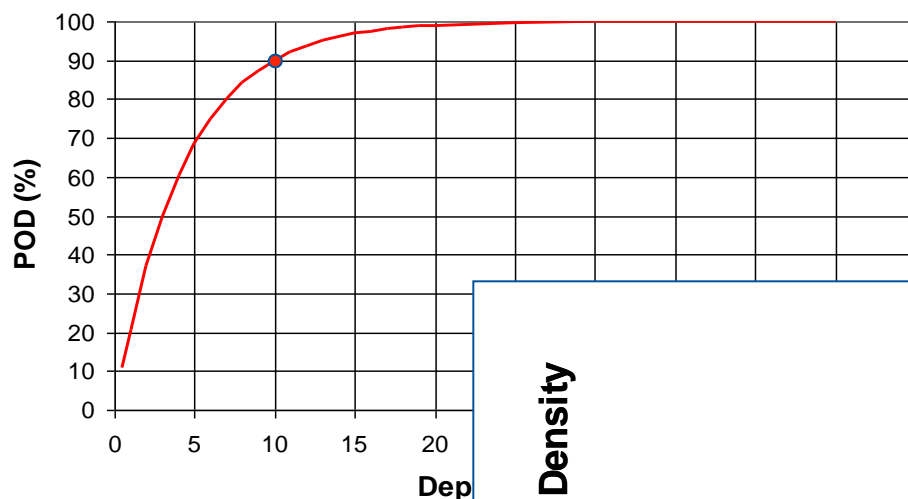
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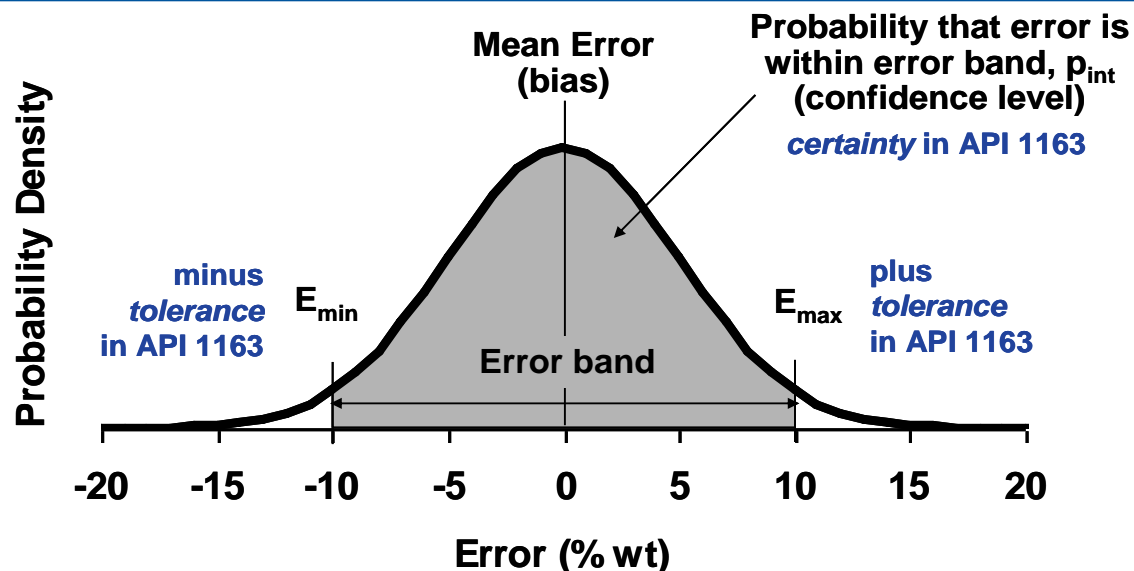
Inspection Uncertainties – ILI Example

Eg: POD = 90% at threshold depth & Threshold depth = 10% wall



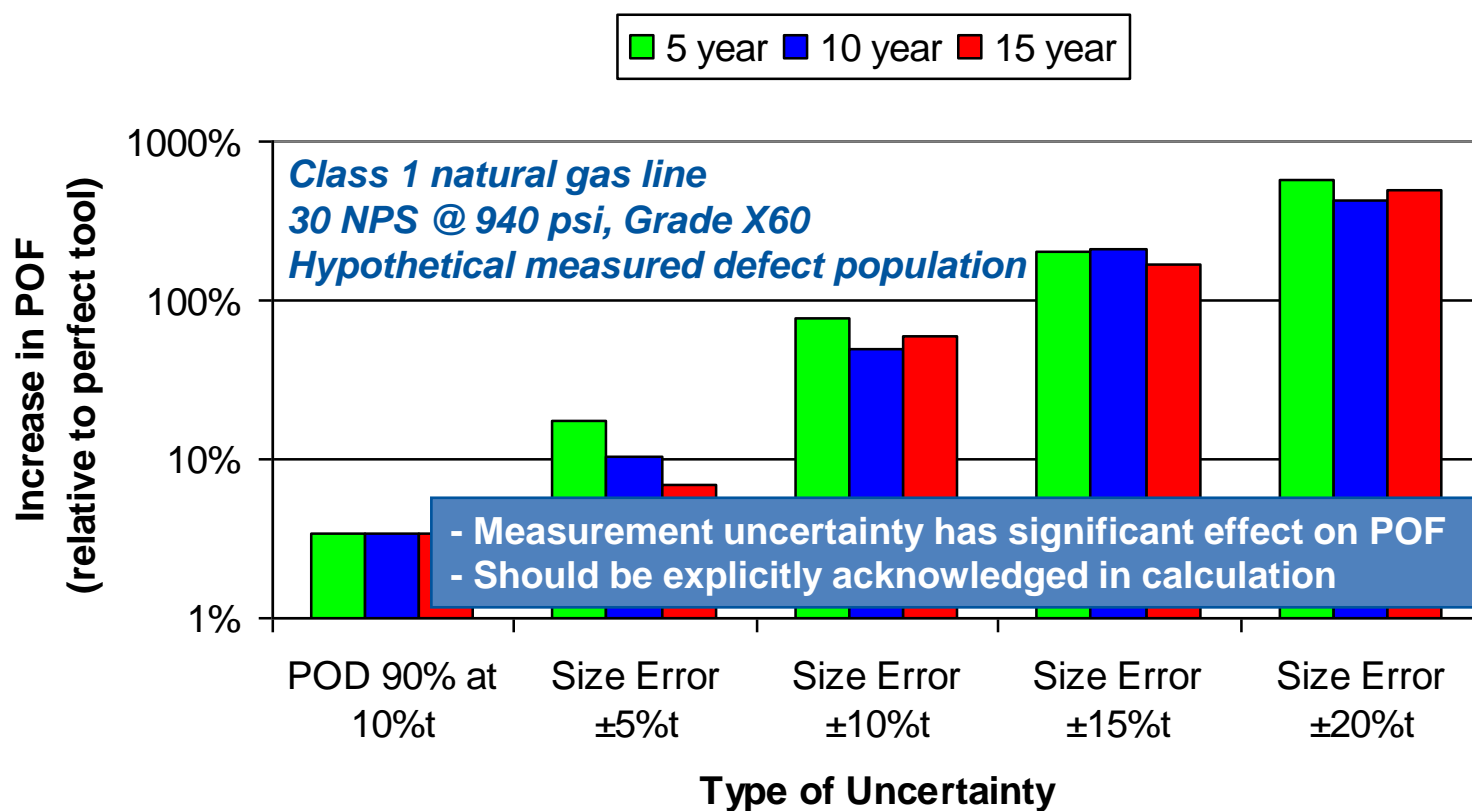
POD - Basis for inferring
density & size distribution of
non-detected features

**Tool tolerance &
Confidence Interval**
– basis for
measurement error
distribution



Inspection Uncertainty – Effect on Probability of Failure

Example – Corrosion failure probability as affected by ILI uncertainty*



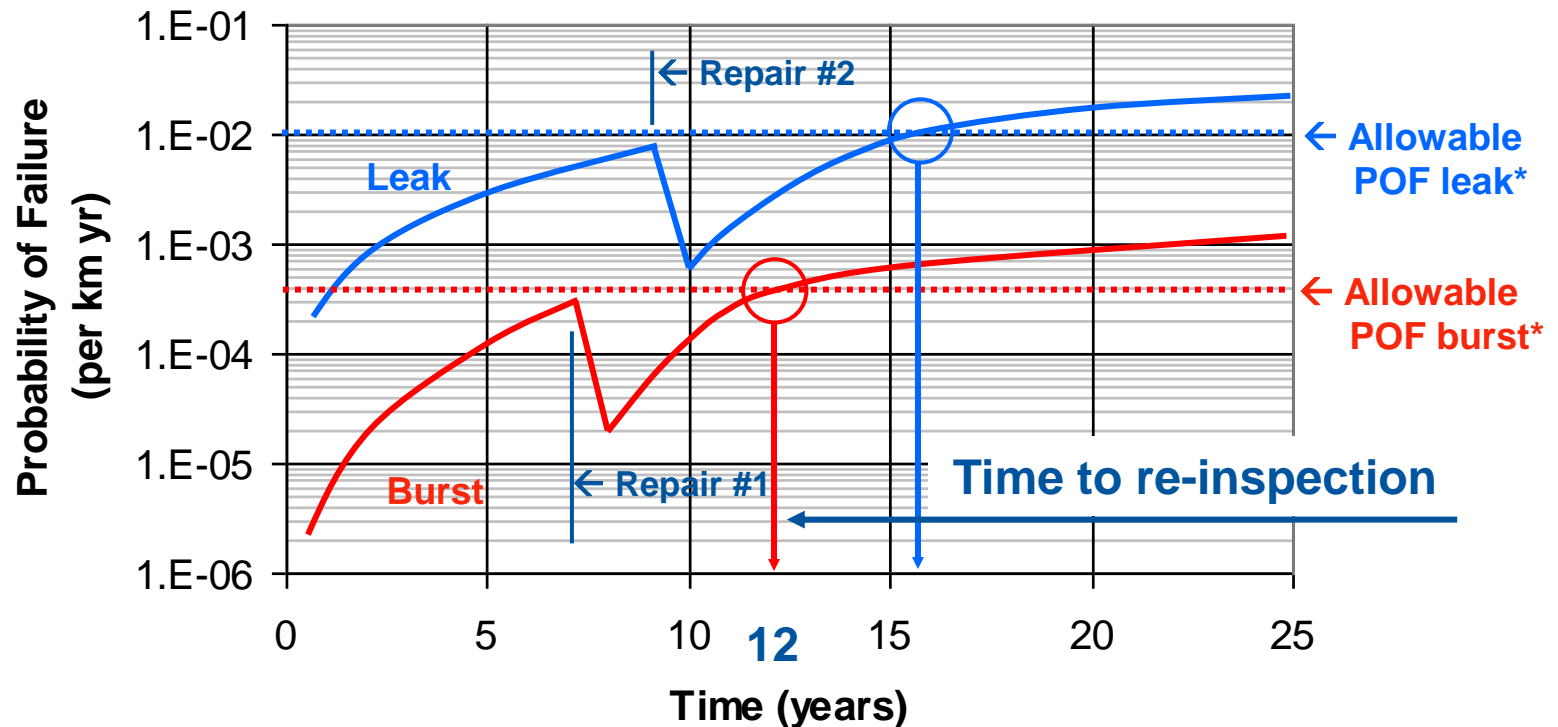
**Growth rate independent of measured defect size*

Effect of Maintenance

- Mitigation philosophy
 - Find and eliminate significant defects before they reach critical size
- Maintenance options, e.g.
 - In-line Inspection
 - Hydrostatic testing
- Maintenance impact
 - Eliminate contribution to POF stemming from defects removed from segment

Impact of Maintenance

Segment reliability versus time – for given evaluation length



**based on risk considerations considering consequences*

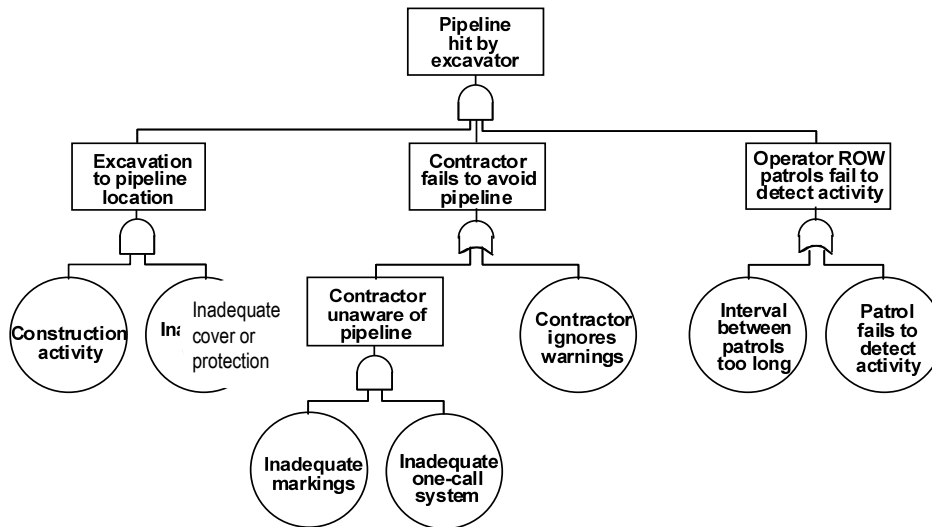
Time-independent damage

(e.g. third-party damage or sudden ground movement)

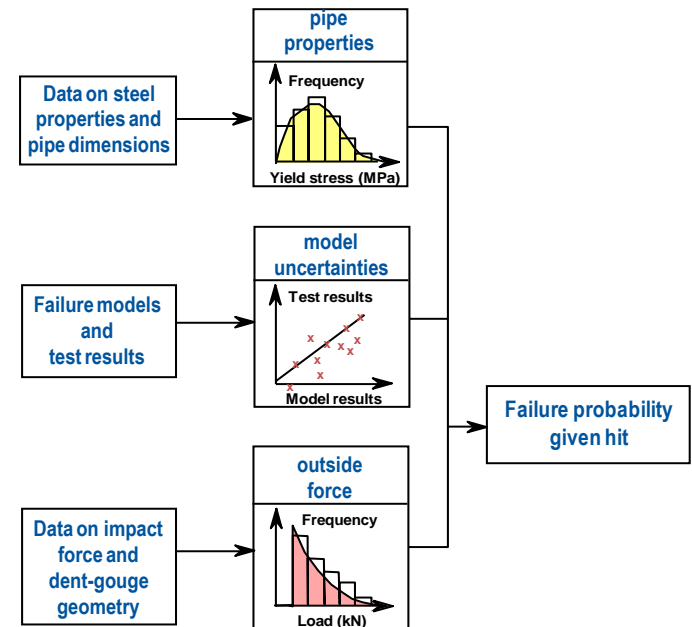
$$\text{Failure rate (per mi-yr)} = \text{Event Frequency (per mi-yr)} \times \text{POF per event}$$

- Considerations in developing failure rate estimate (e.g. 3rd party dmg)
 - Event occurrence frequency \leftarrow fault tree model
 - Likelihood of excavation activity (given land use) and effectiveness of damage prevention measures (e.g. signage, ROW condition, one-call system, patrol frequency, burial depth, mechanical protection) are reflected in estimate
 - Failure given event \leftarrow structural reliability model
 - Failure given hit can reflect uncertainty on damage caused by event, variability in pipe properties, and accuracy of failure prediction model
- Ability to reflect impact of maintenance (e.g. 3rd party dmg)
 - Effect of changes in damage prevention measures and/or modified operating pressure are directly reflected in probability estimates

Calculate equipment impact failure probability

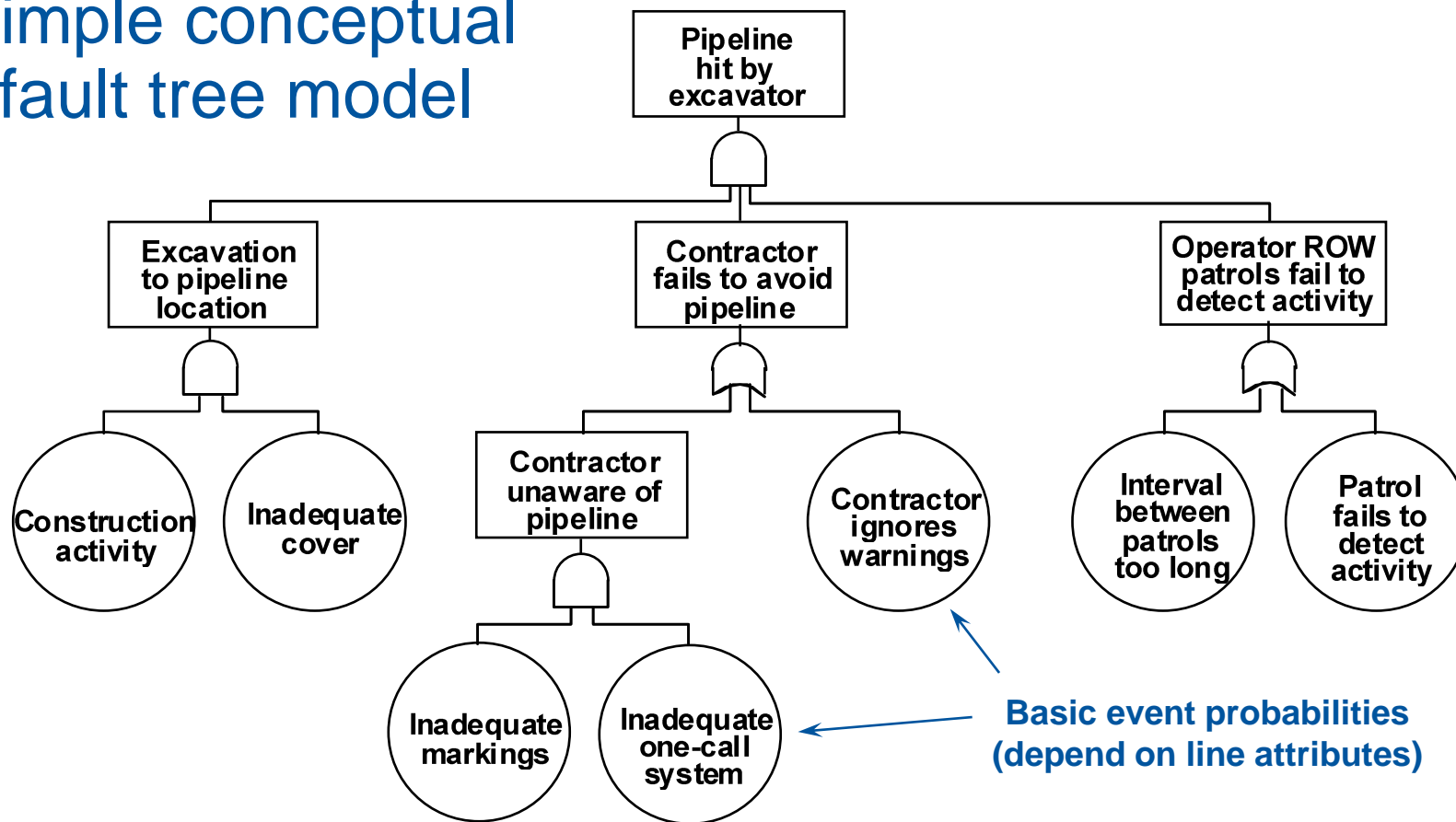


Hit Frequency
(inductive logic model – fault tree)



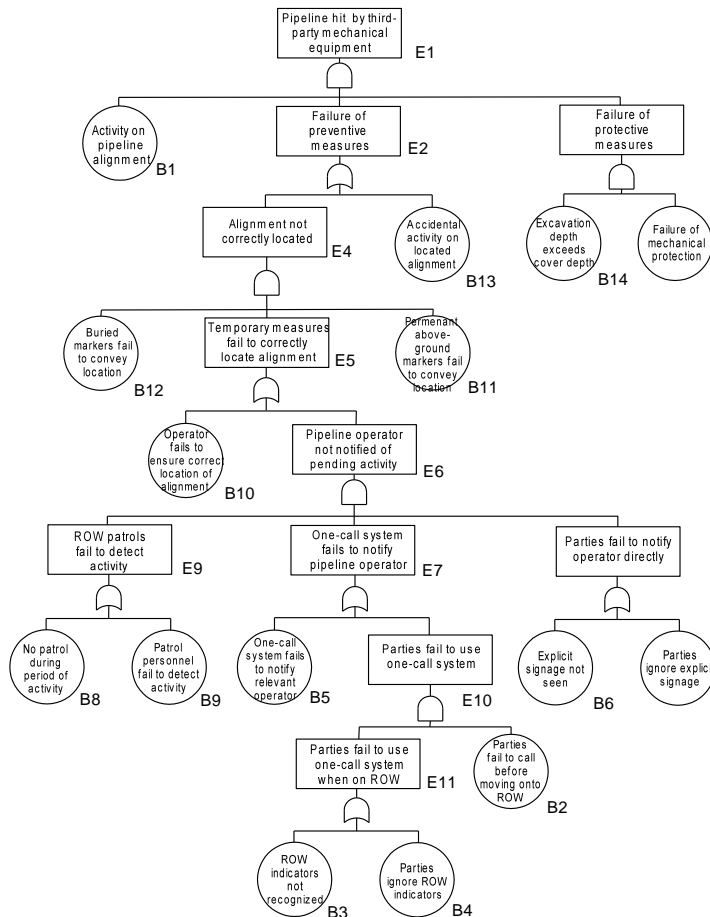
Failure given Hit
(structural reliability models for puncture or dent-gouge)

Simple conceptual fault tree model



Calibrated using historical data
and/or models (e.g. DIRT data)

Actual fault tree model



Can reflect hit frequency impact associated with wide range of system attributes and damage prevention measures

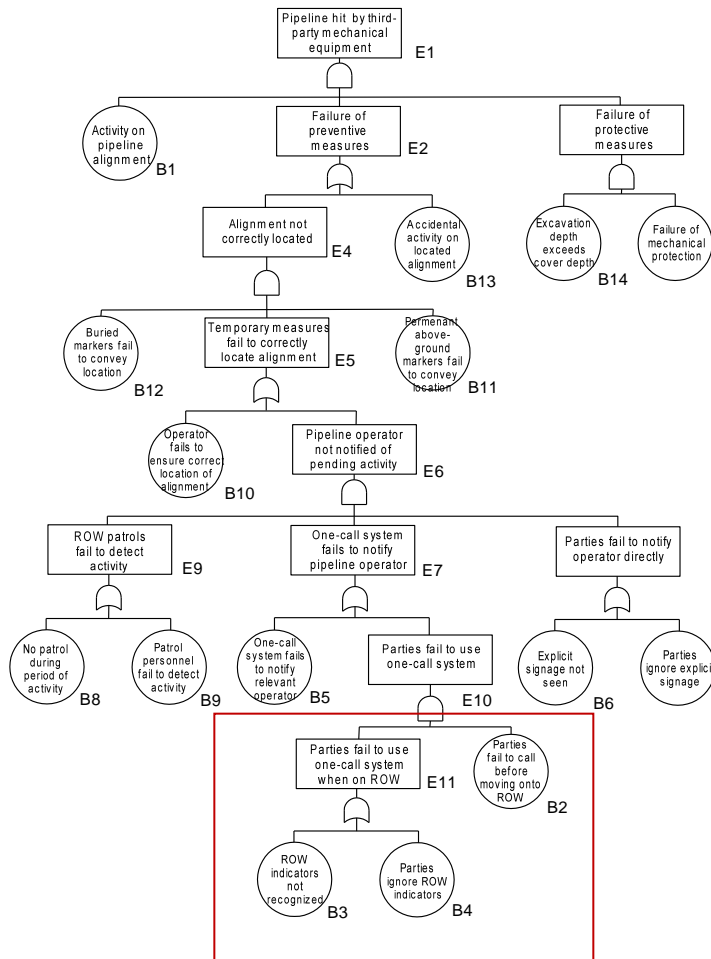
Detailed fault tree considerations

- land use & presence of crossings
- depth of burial
- one call system type
- dig notification requirement
- dig notification response
- public awareness level
- right-of-way indication
- alignment markers - explicit signage
- alignment markers - above ground
- alignment markers - buried
- surveillance method / interval
- mechanical protection

Effect of Maintenance

- Mitigation philosophy
 - Reduce potential for line hits
- Maintenance option examples
 - ROW condition and surveillance enhancement
 - Increased signage/markers
 - Public awareness improvements
 - Increase burial depth
 - Introduce mechanical protection
- Maintenance impact
 - Reduce hit frequency → reduce failure probability proportionately

Actual fault tree model



Can reflect hit frequency impact associated with wide range of system attributes and damage prevention measures

Detailed fault tree considerations

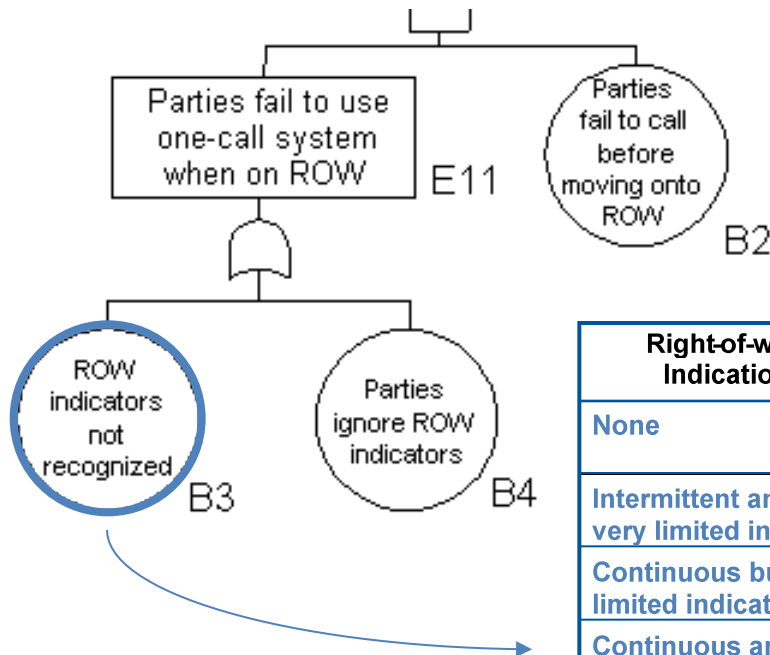
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- mechanical protection

Effect of Damage Management

Attribute changes affect basic event probabilities

→ hit frequency

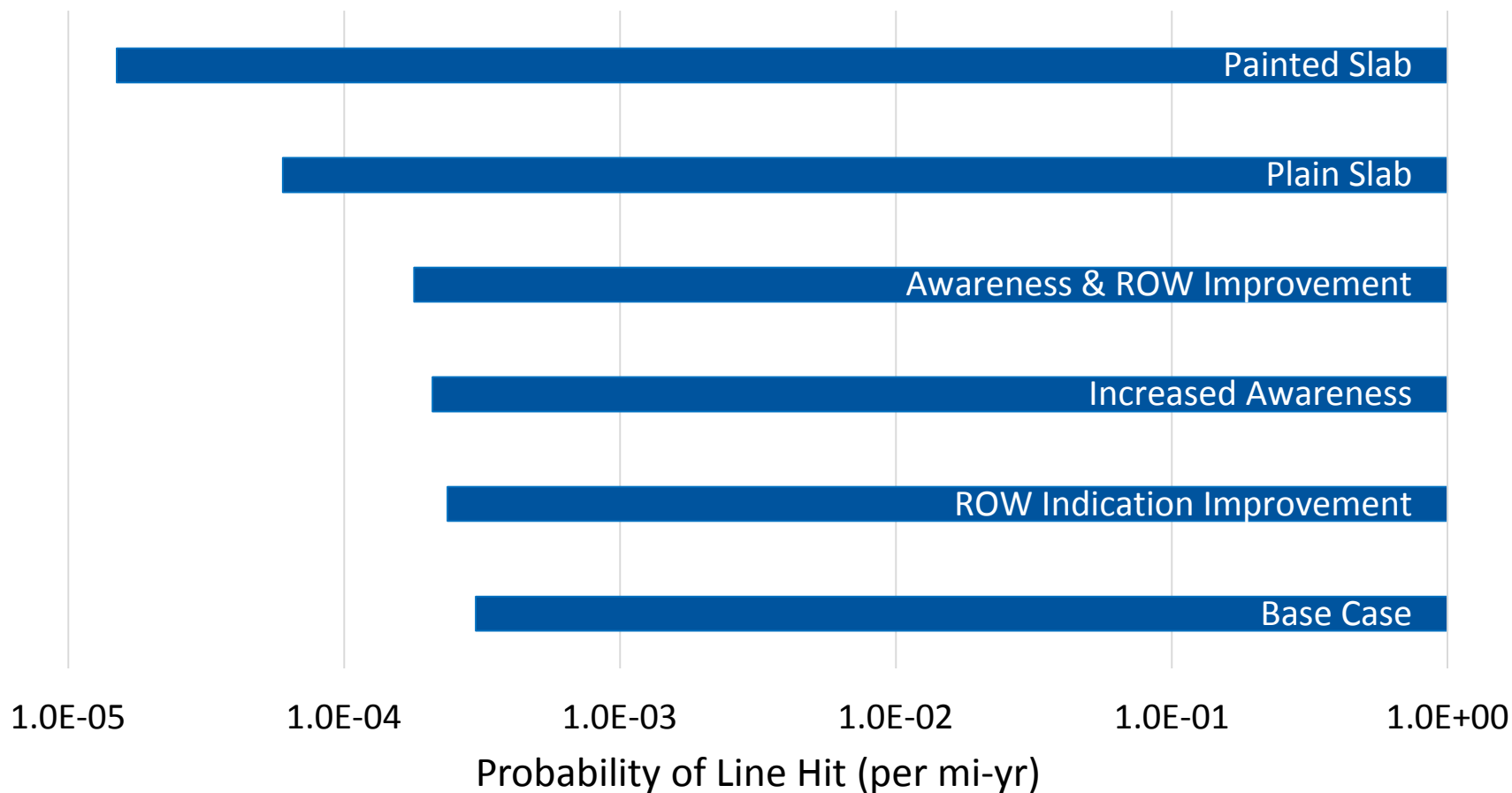
→ failure rate



Right-of-way Indication	Public Awareness Level		
	Below average	Average	Above average
None	1.0	1.0	1.0
Intermittent and/or very limited indication	0.87	0.65	0.43
Continuous but limited indication	0.47	0.35	0.23
Continuous and highly indicative	0.21	0.16	0.11

Probability that ROW indicators are not recognized

Effect of Damage Management



Model Based Approach - Summary

- **Benefits**

- Sound basis for threat-specific, line-specific probability estimates
- Framework for consideration of significant sources of uncertainty
- Can reflect maintenance actions & damage prevention measures

- **Implementation considerations**

- Models require significant development effort
 - Incentive to leverage previous work and/or standardize
- Data requirements not insignificant
 - This data is the basis for objective estimates of failure probability, worth the effort to collect and interpret

Probability Estimation Based on Structural Reliability Models

- Feasibility

- Structural reliability methods and models for specific pipeline integrity threats have been under development for more than 20 years (JIPs & PRCI → Reliability Based Design and Assessment, RBDA)
- Many models in public domain, some in Annex O of CSA Z662

- Validity

- Model development activities have included calibration/validation exercises wherein a suite of models were used to hindcast historical failure rates for the existing North American transmission pipeline network – agreement shown to be good

- Questions and comment welcome